



Equipment Engineering and Quality Assurance Technical Specification

Specification:
EE&QA-886

OCS Inspection Car Consist Procurement

Appendix F: Carbody and Truck Structural Analysis and Testing

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Appendix F

Carbody and Truck Structural Analysis and Testing (If Applicable)



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1 CARBODY DESIGN, ANALYSIS AND TESTING

- 1.1 New designs or substantially modified existing designed carbodies require analysis and testing and shall comply with requirements of this Appendix F.
- 1.2 A Stress Analysis and Test Plan (SATP) for the carbody shall be submitted for MBTA approval. If the test plan includes testing to verify the analysis results, the maximum allowable stress for the loading in this section may be the yield strength of the material for proof loads and the allowable limits for fatigue. The Contractor may propose limiting the stresses to 87% of these levels and foregoing testing, subject to MBTA approval.
- 1.3 The Contractor shall submit a Stress Analysis Report for MBTA review prior to commencing manufacture of any carbody structural parts. [CDRL]
 - 1.3.1 The carbody stress analysis shall include a Finite Element Analysis (FEA), as well as manual and computerized calculations of the stresses in joints, joint elements, and other important elements not included in the FEA.
 - 1.3.2 The stress analysis shall include all equipment weighing over 150 lbs., including equipment attachments, and supporting structure. Stress analyses for supports for items weighing less than 150 pounds may be requested for review at the discretion of the MBTA.
 - 1.3.3 At a minimum, the Stress Analysis Report shall include:
 - 1.3.4 A structural diagram (layout) of the carbody.
 - 1.3.5 Diagrams displaying, for each load case, externally applied loads to the carbody, and boundary conditions.
 - 1.3.6 Calculated stresses, allowable stresses, and margins of safety for all elements for all specified loading conditions.
 - 1.3.7 An analysis showing compliance with each design load and condition.
 - 1.3.8 A tabulation of the Contractor's selection of allowable fatigue stress ranges and calculated fatigue stress ranges for structural members which are critical in fatigue. If tests are conducted to provide the allowable fatigue stress ranges, the entire test report shall be submitted. This report shall show the test procedure, raw data as well as reduced data, and summary.
 - 1.3.9 MBTA may also require submittal of FEA input and output files to better understand the analysis, if required.
 - 1.3.10 The carbody stress analysis shall include a Finite Element Analysis (FEA), as well as manual and computerized calculations of the stresses in joints, joint elements, and other important elements not included in the FEA.
- 1.4 The approved Stress Analysis Report shall be a prerequisite for approval of the structural test procedures required by this Specification and shall be used as an aid in determining strain gage locations. Not less than 30 calendar days shall be provided in the Contractor's schedule for the



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MBTA's review of the Contractor's first submittal of its stress analysis report, and any subsequent submittals of corrected versions.

- 1.5 Based on the vendors weld training, documentation and processes, the weld quality testing during fabrication might vary. Weld plan and processes are subject to MBTA approval.
- 1.6 During fabrication, staged first article inspections are required so that MBTA representatives can be present. The FAI plan shall be approved by MBTA before fabrication starts
- 1.7 Carbody testing shall be performed according to an approved procedure and test reports shall be submitted for approval.
- 1.8 Following carbody tests, the Contractor shall submit a Carbody Test Report for MBTA approval, presenting the test results compared with the corresponding stress analysis results. This information shall be tabulated for each test. [CDRL]
- 1.9 The tables shall compare strains measured (stresses calculated) from the test strain gauge readings with analytical strains (stresses) from the FEA, and show the percent difference between the two values.
- 1.10 The test report shall indicate compliance with the acceptance criteria for correlation between test and analytical results as approved in the Stress Analysis and Test Plan.
- 1.11 The test report shall include a copy of the current calibration certificate for every instrument and gauge to be used during the test.
- 1.12 If the analysis results do not agree with the test results within the acceptance criteria, the Contractor shall revise the stress analyses, update the FE model, and re-run all FE analyses. This process shall be repeated until agreement of results is within the specified acceptance criteria. All manual analyses using data from the FEA shall be recalculated using the corrected values. The stress analysis report shall be revised and re-submitted.

2 TRUCK DESIGN, ANALYSIS AND TESTING

2.1 Static Strength

- 2.1.1 The basis for determining maximum load variation shall include forces resulting from equipment load, track shocks and forces, motor torque, friction brakes, dampers, and any possible combination of these forces when operating under all possible track conditions in Section 2 at speeds up to the maximum safe speed. Note that the above loads are presented as design minimums, and the Contractor is required to determine for itself if higher loads are required to reflect the anticipated service conditions.
- 2.1.2 The static strength design condition for the truck frame and truck bolster, if applicable, shall be based on the truck's share of a design load equal to the vehicle's maximum gross weight minus the weight of the trucks, with consideration for lift system loading.
 - 2.1.2.1 The vertical load on the truck shall not be less than the truck's share of the design load, augmented by the weight transfer effects such as tractive effort, braking reactions, or lift system loading.



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- 2.1.2.2 The longitudinal load, applied at the center of gravity of the car, shall not be less than the maximum possible instantaneous braking effort at the vehicle's maximum gross weight and 50% adhesion.
- 2.1.2.3 The lateral load, applied at the center of gravity of the car, shall be appropriate for the anticipated service conditions, but in no case less than 0.25g.
- 2.1.2.4 Accessory loads, such as those from brake units and traction motors, shall represent maximum steady state conditions; for example, maximum motor torque and brake unit weight, and maximum brake unit reaction and motor weight, or the worst combination (brake blending) of both. Damper loads shall vary between plus and minus twice the maximum damper load for each direction.
- 2.1.2.5 Equipment loads shall be calculated using the exceptional accelerations specified by Section 2 of the Technical Specification.
- 2.1.2.6 Under these combined conditions, the maximum stresses at any location in the truck frame and bolster shall not exceed 50% of the material yield strength. Local zones greater than the allowable stress will be reviewed on a case-by-case basis, provided that the overall stability of the truck is not affected. Based on this review, the MBTA will determine the acceptability of these areas.
- 2.1.3 Independently evaluated exceptional loads including the lateral load that would cause vehicle overturning, short circuit motor torque, and maximum spring force in the brake actuators must be analyzed, and the maximum stress at any location in the truck frame and bolster shall not exceed 75% of the material yield strength. Local zones greater than the allowable stresses will be reviewed on a case-by-case basis, provided that the overall stability of the truck is not affected. Based on this review, MBTA will determine the acceptability of these areas.

2.2 Fatigue Strength

- 2.2.1 The Contractor shall propose fatigue design loads for the truck frame and bolster, based on the following conditions:
 - 2.2.1.1 The mean vertical load on a truck shall be the truck's share of the design load and the vertical load shall vary about the mean vertical load by $\pm 25\%$.
 - 2.2.1.2 The lateral load shall vary between 15% of the mean vertical load acting towards one side of the truck and 15% of the mean vertical load acting towards the other side of the truck.
 - 2.2.1.3 The longitudinal load shall vary between 15% of the mean vertical load acting towards one end and 15% of the mean vertical load acting towards the other end.
 - 2.2.1.4 The lateral and longitudinal loads shall act as if they were applied at the center of gravity of the carbody with resulting vertical loading applied to the bolster or truck frame as appropriate.
 - 2.2.1.5 Accessory loads shall vary between $\pm 100\%$ of their maximum steady-state values: motor under maximum braking torque and brake unit reaction under Full Service Brake



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application. Damper loads shall vary between $\pm 125\%$ of the maximum damper load for each direction.

2.2.1.6 Equipment loads shall be calculated using the fatigue accelerations specified by Section 2 of the Technical Specification.

2.2.1.7 All loads shall be applied with the phasing to produce the worst possible stress combination. Under these conditions, stresses shall not exceed the allowable fatigue endurance limits.

2.2.2 Fatigue allowable stress range and mean stress for truck materials shall not exceed endurance limits provided in MBTA approved industry standards. Fatigue allowable stress range for welded connections shall not exceed the requirements of AWS D1.1 or MBTA approved industry standard.

2.2.2.1 The Contractor may also propose for MBTA approval fatigue endurance limits based on testing performed by the Contractor.

2.2.2.2 All fatigue endurance limits shall be taken for at least 10 million cycles.

2.2.3 The Contractor shall submit its chosen static and fatigue allowable values, whether published or test values, to the MBTA for review and approval with the Truck Stress Analysis and Testing Plan.

2.3 Equipment Mounting Strength

2.3.1.1 All equipment shall have sufficient attachment strength to withstand the exceptional and fatigue accelerations specified in Section 2 of the Technical Specification.

2.4 Stress Analysis

2.4.1 This section describes the stress analysis and testing requirements for the truck and bolster, if applicable. For any portion of the proposed design which is based on a service-proven truck design, the Contractor may provide data from previous tests, historical data from operations, or prior stress analyses as required to satisfy the corresponding portion of these requirements.

2.4.2 A Truck Stress Analysis and Testing Plan, including the information listed below, shall be submitted for MBTA review and approval. It shall include an outline of the procedure the Contractor will use to analyze and test the design of the truck. The Truck Stress Analysis and Testing Plan must be approved prior to the submittal of the Truck Stress Analysis Report.
[CDRL]

2.4.2.1 Derivation of the static and fatigue loads to be applied.

2.4.2.2 Description of the major assumptions used in the analysis.

2.4.2.3 References to analysis and test document report numbers.



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- 2.4.2.4 Table of loads to be used for static analysis and test, with load magnitudes, points of application, and boundary conditions.
- 2.4.2.5 Table of loads to be used for fatigue analysis and test, with load magnitudes, points of application, boundary conditions, and phasing.
- 2.4.2.6 List of allowable stresses for each load condition.
- 2.4.2.7 Description of the analysis to be used for each load condition.
- 2.4.2.8 Diagrams of load applications, boundary conditions, and expected reactions.
- 2.4.2.9 Detailed plan for validating analytical results using test results, including acceptance criteria for the correlation between test measurements and analytical results.
- 2.4.2.10 Table of material properties showing the engineering properties of each grade and temper of each material used in the truck structure. This table shall include the material designation, yield strength, ultimate strength, elongation, Young's modulus for tension, and compression and shear elastic modulus. In each case, minimum-guaranteed values from the specifications for the corresponding grade and heat treatment of the material shall be used. Materials, grades, and tempers not used in the truck construction shall not be included in the tables.
- 2.4.3 The Contractor shall submit for MBTA approval, prior to truck and bolster manufacturing and testing, a stress analysis report of the truck structural components including, but not limited to, the truck frame, truck bolster, and other load bearing parts. [CDRL]
 - 2.4.3.1 The stress analysis shall consist of, as a minimum, a finite element model, and a finite element analysis of the global structure, including all equipment and attachments, with a classical analysis of all connections, supplemented as necessary by manual or computerized calculations. The finite element model shall be developed using an industry accepted program.
 - 2.4.3.2 The stress analysis report shall include the following information:
 - 2.4.3.2.1 A structural diagram (layout) of the truck frame and bolster, showing all member locations and shapes and indicating the material and thickness of each. Methods of joining shall be defined. Drawing references shall be provided.
 - 2.4.3.2.2 An analysis showing compliance with each design load and condition.
 - 2.4.3.2.3 The calculated stresses, allowable stresses, and margins of safety for all elements for all specified loading conditions.
 - 2.4.3.2.4 A table showing locations where the margin of safety is less than 0.5 along with the design or operating conditions (loads) which cause those stresses.
 - 2.4.3.2.5 The finite element analysis shall show deflections in all three axes imposed over the deflected shape, maximum and minimum principal stress contour plots, maximum



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and minimum principal stress vector plots showing the direction of the principal stresses, and Von Mises stress plots.

- 2.4.3.2.6 A tabulation of the Contractor's selection of allowable fatigue stress ranges and calculated applied fatigue stress ranges.
- 2.4.3.2.7 References shall be supplied for all formulas, calculation procedures, material strengths and like items cited where these items appear.
- 2.4.3.3 If tests are conducted to provide the allowable fatigue stress ranges, the entire test report shall be submitted. This report shall show the test procedure, raw data as well as reduced data, and summary.
- 2.4.3.4 The information derived from the analysis shall be used to determine strain gauge locations and other criteria for the truck static tests. The locations of all strain gauges shall be shown on plots of the FEA truck and bolster mesh with dimensions.
- 2.4.3.5 The manual calculations shall supplement the finite element analysis and include analysis for the axles, all bolted joints, and other connections and structural details as appropriate that are not readily evaluated in the FEA. The conventional analysis format consists of a title, sketch of items to be analyzed with dimensions and applied forces, drawing references, material properties, allowable stress, and detailed stress calculations with references and conclusions. Forces and moments for the analysis can be obtained from the FEA.
- 2.4.3.6 The analysis shall be updated if any changes are made to the truck design.
- 2.4.4 The Contractor shall submit a separate analysis of truck and bolster welds and welded connections that shows their calculated fatigue stress ranges and fatigue classifications according to AWS D1.1 or MBTA approved industry standard. [CDRL]
 - 2.4.4.1 This analysis shall account for all welding under all specified loading conditions, including welds attaching brackets, studs, and holders, in addition to the major structural welds.
 - 2.4.4.2 The analysis shall include drawings of the truck weld layout with the fatigue strength classification indicated for each weld.
- 2.4.5 Truck static testing shall be performed on the first production truck frame to validate the truck stress analysis. At least 30 days prior to performing the static testing, the Contractor shall submit a test procedure for MBTA approval. The test procedure shall, at a minimum, contain the following items. [CDRL]
 - 2.4.5.1 Description of how and with what equipment the specimen is to be loaded and in what load increments, the type and location of strain gauges and the location of deflection gauges. Drawings and sketches shall be included to clarify the text. Also included shall be the drawings showing the test fixture, the specimen installed in the fixture, and location of load application points.



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- 2.4.5.2 The test procedure shall include a step-by-step instruction describing how load is applied, the load at each step, when to record data, and the place where authorization to proceed is to be obtained from the MBTA representative.
- 2.4.5.3 Description of the accuracy of each type of measurement equipment used.
- 2.4.5.4 List of conditions under which the test shall be terminated, including maximum allowable strains or displacements.
- 2.4.5.5 Each test procedure shall contain a table of predicted strain (or stress) at selected strain gauge locations. This table shall list the strain gauge number, predicted strain (or stress) from the stress analysis, the location of the gauge, a space to enter the measured strain (or stress), and a space to enter the calculated percent difference.
- 2.4.6 Following truck static testing, the Contractor shall submit a Truck Test Report for MBTA approval, presenting the test results compared with the corresponding stress analysis results. This information shall be tabulated for each test. [CDRL]
 - 2.4.6.1 The tables shall compare strains measured (stresses calculated) from the test strain gauge readings with analytical strains (stresses) from the FEA, and show the percent difference between the two values.
 - 2.4.6.2 The test report shall indicate compliance with the acceptance criteria for correlation between test and analytical results as approved in the Stress Analysis and Test Plan.
 - 2.4.6.3 The test report shall include a copy of the current calibration certificate for every instrument and gauge used during the test.
 - 2.4.6.4 If the analysis results do not agree with the test results within the acceptance criteria, the Contractor shall revise the stress analyses, update the FE model, and re-run all FE analyses. This process shall be repeated until agreement of results is within the specified acceptance criteria. All manual analyses using data from the FEA shall be recalculated using the corrected values. The stress analysis report shall be revised and re-submitted.